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A HIGH SPEED FIBER TO PHOTODETECTOR INTERFACE

FIELD OF THE INVENTION

5   The present invention generally relates to electro-optic devices and more particularly relates to package assemblies for interfacing electro-optical devices with optical fibers.

BACKGROUND

10   The proliferation of optical communication networks intended for subscribers has created a strong demand for low-cost and compact optical assemblies. The costs of an optical subassembly (OSA) increases with the number of components that combine to form the subassembly. In order to reduce the number of component

15 parts of an optical assembly, attention has recently been directed to lensless, butt-coupling methods for interfacing an electro-optic device and an optical waveguide. The precision of alignment that is required between the end of an optical waveguide, and an optoelectronic device varies with application.

20   For example, on the receiving side of an optical communication system, a received optical signal is opto-electrically converted into an electrical signal by a photodetector such as a photodiode, and information is reproduced according to the electrical signal obtained. Alignment

25 difficulties on the receiver side of an optical communication system may therefore be introduced by characteristics of both the optical waveguide and the photodetector.

The alignment difficulty may generally be addressed by making a detector "artificially" larger than it needs to be,

30 resulting in slower photodetectors with inherently larger rise times, fall times, and settling times. Larger photodetectors may therefore limit system level bandwidth which ultimately limits transmission data rates. The bandwidth of a photodetector is generally determined by the transit time of the photo-generated

35 carriers in the absorption region and the RC time constant. The

inherently lower bandwidth, for larger photodetectors, is caused by higher shunt resistance and larger shunt capacitance of the photo conductive areas of the detectors. More rapid response requires a smaller electrostatic capacitance at the depletion layer. The electrostatic capacitance decreases with decreasing depletion region area. Therefore, the diameter of the light receiving portion of high speed photodetectors are typically restricted to minimize the capacitance of the device.

However, optical beams emanating from an optical fiber typically have a relatively wide cross-sectional area that requires a wide depletion region. For example, the divergent beam size of existing fiber to photodetector interface assemblies that do not include focusing elements are typically on the order of about 25μm, limiting their utility to data rates below about 10Gbps. Therefore, it would be advantageous to provide a compact, high speed optical subassembly that does not require a focusing element to efficiently couple light into a photodetector.

SUMMARY OF THE INVENTION

In an exemplary embodiment of the present invention, an optical receiver includes a photodetector, adapted to receive an incoming optical signal from a fiber having a distal end with a slanted end face, wherein a portion of the fiber cladding material on the exiting light side of the slanted end face has reduced thickness to allow the photodetector to be more closely coupled to the slanted end face.

In another aspect of the present invention, an optical receiver includes a housing adapted to receive a distal end of a fiber having a slanted end face for reflecting the received light along a first optical path, a photodetector mounted in the housing so that the reflected light beam is incident on the photodetector, the photodetector having a photodetecting portion responding to the light beam incident on said photodetector and

wherein the fiber cladding material along the first optical path has reduced thickness to allow the photodetector to be more closely coupled to the slanted end face of the fiber.

In another aspect of the present invention a method for receiving a high speed optical signal includes the steps of coupling a distal end of an optical fiber having an angled end face with a housing, reflecting a received signal off the angled end face along a first optical path, wherein the fiber cladding material in the first optical path has reduced thickness and coupling a photodetector to the housing so as to receive the reflected optical signal.

In a further aspect of the present invention an optical receiver includes a housing adapted to receive a distal end of a fiber, a focusing lens, optically aligned with the distal end of the fiber for focusing received signal into a first end of a fiber guide wherein a second end of the fiber guide comprises a slanted end face adapted to uniformly illuminate a photodetector.

In a further aspect of the present invention an optical receiver includes a housing adapted to receive a distal end of an optical fiber, a focusing lens, optically aligned with the distal end of the optical fiber for focusing received signal into a first end of a fiber guide wherein a second end of the fiber guide comprises a slanted end face adapted to uniformly illuminate a photodetector.

It is understood that other embodiments of the present invention will become readily apparent to those skilled in the art from the following detailed description, wherein it is shown and described embodiments of the invention by way of illustration of the best modes contemplated for carrying out the invention. As it will be realized, the invention is capable of other and different embodiments and the details are capable of modification in various other respects, all without departing from the spirit and scope of the present invention. Accordingly, the drawings

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and detailed description are to be illustrative in nature and not restrictive.

5   BRIEF DESCRIPTION OF THE DRAWINGS

These and other features, aspects, and advantages of the present invention will become better understood with regard to the following description, appended claims, and accompanying drawings, in which:

10   FIG. 1 is a plan view of an exemplary optical receiver having a photodetector and transimpedance amplifier coupled to a circuit board in accordance with an exemplary embodiment of the present invention;

FIG. 2 is cross section of the photodetector coupled to the

15   circuit of FIG. 1 in accordance with an exemplary embodiment of the present invention;

FIG. 3 is a cross section wherein the circuit board of FIG. 1 is mounted in a metallic housing comprising a bottom plate with four side walls)and a top close out plate in accordance with an

20   exemplary embodiment of the present invention;

FIG. 4 is a cross section of a conventional fiber to photodetector interface;

FIG. 5a is a cross section of a fiber to photodetector interface wherein a portion of cladding material on exiting light

25   side of the slanted end face has reduced thickness to allow the photodetector to be more closely coupled to core of said fiber in accordance with an exemplary embodiment of the present invention;

FIG. 5b is an end view of the fiber to photodector interface

30   of FIG. 5a illustrating the portion of cladding material on exiting light side of the slanted end face has reduced thickness in accordance with an exemplary embodiment of the present invention;

FIG. 6 graphically characterizes the beamwidth versus

35   cladding thickness for the fiber to photodetector interface of

FIG. 5a in accordance with an exemplary embodiment of the present invention;

FIG. 7 graphically illustrates the typical operation data rate of an photodetector as a function of diameter of photodetector active area;

FIG. 8 is a cross section of a photodetector flip chip mounted to a circuit for use in a backside illuminated fiber to photodetector interface in accordance with an exemplary embodiment of the present invention;

FIG. 9 is a cross sectional of an exemplary fiber interface for the backside illuminated photodetector of FIG. 8 in accordance with an exemplary embodiment of the present invention;

FIG. 10 is an exemplary process for designing a high speed optical interface in accordance with an exemplary embodiment of the present invention;

FIG. 11 is a cross section of a conventional fiber to photodetector interface including a focusing system having multiple lenses for imaging the end face of the fiber onto the photodetector;

FIG. 12 is a cross section of a fiber to photodetector interface including a focusing system having a slant ended fiber guide for reflecting a uniformly reflecting a received beam onto a photodetector in accordance with an exemplary embodiment of the present invention;

FIG. 13 is a perspective view of the fiber to photodetector interface of FIG. 12 wherein the interface housing includes a silicon substrate having a recess in the form of a v-groove that is adapted to retain the fiber guide in accordance with an exemplary embodiment of the present invention;

FIG. 14 is an exemplary process for designing the high speed optical interface illustrate in FIG. 12 in accordance with an exemplary embodiment of the present invention; and

FIG. 15 is a cross section illustrating additional details of the focusing system illustrated in FIG. 12 in accordance with an exemplary embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

An exemplary embodiment of the present invention provides an apparatus and method for interfacing a high speed photodetector with an optical fiber. In order to appreciate the advantages of the present invention, it will be beneficial to describe the invention in the context of an exemplary optical receiver module.

Referring to FIG. 1, an exemplary optical receiver module may include a photodetector 10 and a transimpedance amplifier (TIA) 12 mounted on a circuit board 14. The described exemplary optical receiver module may further include a housing for receiving an optical fiber lying parallel to the circuit board (see FIG. 3). In an exemplary embodiment the photodetector 10 may be planar having a first surface oriented to receive light normal to the longitudinal axis defined by the fiber core. A source (power supply) pattern 16 and a ground pattern 18 may also be formed on the circuit board 14. The source (power supply) pattern 16 may be coupled to a source microstrip 20. The ground pattern 18 may be coupled to a ground microstrip 22.

In the described exemplary embodiment, an annular ohmic contact 24, formed on an upper surface of the photodiode 10, is coupled to an input terminal of the TIA 12 via conventional wire bonding techniques. Wire bonds may be formed from aluminum or gold, with small alloying additions to achieve the desired handling strength.

The wire bonds between the photodector and the transimpedance amplifier may introduce a parasitic inductance that tends to reflect the signal generated by the photodetector back to the photodetector. The inductance generally increases with increasing wire length. Therefore, in one embodiment an

interconnect metal (not shown) may be formed and patterned on an upper surface of the photodetector. The low resistance metalization layer may extend away from the annular ohmic contact to form a coplanar contact pad (not shown). The contact pad is preferably located so as to reduce the length of the wirebond coupling between the photodetector and transimpedance amplifier.

In operation, when the light beam is incident on the light receiving area of the photodetector, electron-hole pairs are generated. A bias voltage is applied across the ohmic contacts so that electrons and holes are moved by a bias electric field to bring about a flow of electric current having an intensity proportional to the intensity of the incident light. The output current signal of the photodetector may be coupled to an input of the transimpedance amplifier. The transimpedance amplifier converts the current signal to an output voltage signal.

An exemplary optical receiver module may further include a capacitor 26 coupled between the source pattern 16 and the ground pattern 18. The capacitor 26 shunts transients past internal receiver components that may be damaged by high voltages. In addition, the external capacitor substantially reduces the effects of transient noise on the output signal.

Referring to the cross section of FIG. 2, the photodetector 10 may be coupled to the circuit board 14 by a connection layer 30. The connection layer 30 may be formed from thermoplastic adhesive or solder. In the described exemplary embodiment, a lower side ohmic contact is coupled to a titanium, platinum, gold, etc. contact pad on the circuit board 14. The photodetector in the described exemplary embodiment may comprise a top side illuminated p-i-n photodiode. Therefore, the lower n-type ohmic and contact pad may be coupled to the ground pattern on the circuit board. For this embodiment, it is assumed that the cathode of the photodetector is grounded. Therefore, the photodetector is energized by applying a positive signal to the photodetector. However, it is to be understood that

photodetectors can also be packaged with the anode grounded, in which case a negative signal is applied to the module to energize the photodetector.

In the described exemplary embodiment, an n-type layer 32 is epitaxially grown on an n-type semiconductor substrate 34. The n-type layer 32 is preferably lattice-matched to the substrate 34 and any intervening layers. In an exemplary embodiment, the n-type layer 32 may be formed of InP. The n-type layer 32 may be doped with a suitable dopant, such as, for example, sulfur.

An active absorber region 36 that is absorptive at the wavelength of interest may be epitaxially formed on the n-type layer 32. The active absorber 36 may be formed from InGaAs or other suitable materials known in the art. In an exemplary embodiment a p-type layer 38 is formed on the active absorber layer 36 from InP. The p-type layer may be doped with a suitable dopant such as Zinc.

To electrically contact the photodetector p-type and n-type ohmic contacts 24 and 40 are preferably deposited above the p-type region 38 and below the substrate 34 respectively. The p-type ohmic contact (also referred to as the annular ohmic contact) may be formed, for example, by depositing a p-type metalization, such as gold with 2% beryllium added or a layered structure of titanium/platinum/gold above the p-type layer, defining an annular opening therein by a lithographic masking and lift-off process. The p-type ohmic contact 24 may be deposited by electron beam evaporation. In one embodiment the n-type ohmic contact 24 may be formed, for example, by depositing an n-type metalization such as AuGe/Ni/Au on a lower surface of the substrate.

One of skill in the art will appreciate that the present invention is not limited to a particular photodetector. Rather the present invention may be utilized with a variety of photodetectors known in the art, such as, for example, a metal-

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semiconductor-metal (MSM) photodetector or an avalanche photodiode. Further, the photodetector may be formed from a plurality of group III-V compound semiconductors, such as, for example, GaAs/AlGaAs, InGaAs/AlGaAs or InP/InGaAsP or other direct bandgap semiconductor materials. Therefore, the disclosed exemplary p-i-n photodiode embodiment is simply by way of example and not by way of limitation.

Referring to the cross section of FIG. 3, an exemplary optical receiver may further include a metallic housing comprising a bottom plate 50 with four side walls (two shown 52 and 54) and a top close out plate 56. In the described exemplary embodiment the circuit board 14 may be mounted onto the bottom plate 50 of the housing with a conductive epoxy and connection wires may be coupled to the input power leads as required.

An exemplary housing may further include a sleeve 58 for receiving a distal end 60 of a fiber. In one embodiment a portion 62 of the fiber may be metallized and soldered to a connector 61 that is coupled to the housing within the sleeve 58 to allow the photodetector to be hermetically sealed. Further, the distal end 60 of the optical fiber may be epoxied to the circuit board 14 so that the distal end is aligned with the photodetector 10 in a manner that maximizes the amount of light coupled between the optical fiber and the photodetector. As is known in the art, the optical fiber and photodetector may be actively aligned through a series of adjustment steps. In addition, a coaxial cable 64 or differential voltage leads may provide an output from the optical receiver.

The cross section of FIG. 4 illustrates a conventional lens free interface between a photodetector and a fiber (such as, for example, a SMF-28 fiber). An end face 100 of a distal end of optical fiber 102 is non-perpendicular to the longitudinal axis defined by the fiber core 104. That is to say, the end face 100 of the optical fiber 102 is slanted. As is known in the art the end face of the fiber may be cleaved or polished to provide a

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desired end face angle. The angle of the end face of the fiber
(β) is preferably large enough to ensure that reflected light is
not confined within the fiber and does not propagate back through
5   the cladding toward the transmitter, but is instead directed
toward the photodetector 10. For a typical fiber, the angle of
the fiber end face is preferably greater than about eight degrees
to provide an optical return loss of less than about -55 dB.

In the described exemplary embodiment the end face of the
10   fiber is slanted at an angle that is less than the critical angle
for total internal reflection and is preferably in the range of
about 40-55 degrees. Reflections off the end face of the fiber
create a divergent reflected beam whose width increases with
increasing distance from the slanted end face 100 of the fiber.
15   For efficient optical coupling, the diameter of the light
receiving portion or active area of the photodetector is
preferably equal to or greater than the diameter of the incident
beam. Therefore, for efficient optical coupling, the diameter
of the light receiving portion or active area of the
20   photodetector also increases with increasing separation between
the photodetector and the fiber core or end face.

The beam divergence is bounded in large part by the maximum
angle captured by the core as defined by the critical angle.
Rays traveling at an angle less than the critical angle (see Eq.
25   1 below) are totally internally reflected and guided by the
fiber.

$$\alpha = \cos^{-1} (n_{cladding} / n_{core}) \qquad\qquad (Eq.1)$$

Higher angle rays, on the other hand enter the cladding and
are lost due to high levels of scattering and absorption. For
30   example for a SMF-28 fiber having a cladding refractive index
($n_{cladding} \cong 1.604$) and a core refractive index ($n_{core} \cong 1.6105$) the
critical angle is on the order of about 4.98°.

Referring again to FIG. 4, simple ray tracing or geometrical
optics techniques may be used to approximate the diameter (A+B+C)
35   of a photodetector as a function of the separation between the

fiber core and photodetector, as largely determined by the cladding thickness ($t_{cladding}$). For example, for an end face slant angle $\beta=45°$, and a core thickness (t_{core}) of $9\mu m$ (e.g. SMF-28 fiber) the width B is also equal to $9\mu m$. In addition, for $t_{cladding}$ = $58\mu m$ for a SMF-28 fiber the width A may be approximated by:

$$(t_{cladding} + t_{core}) / \tan \{180-(\beta+\alpha) -\beta\} \qquad \text{(Eq. 2)}$$
$$\cong 5.84647\mu m$$

and the width C may be approximated by:

$$(t_{cladding}) / \tan \{180-(\beta+\alpha) -\beta\} \qquad \text{(Eq. 3)}$$
$$\cong 5.06112\mu m$$

Thus, a photodetector diameter of approximately $19.9075\mu m$ is required for a cladding thickness of $58\mu m$. In operation the beam size will be slightly larger (approximately $4/\pi$ or 1.27 diameter) due to the Gaussian distribution of the beam. Therefore, a photodetector diameter of approximately $25.28\mu m$ may be required for a cladding thickness of $58\mu m$.

Referring to the cross section and end views of FIGS. 5a&b respectively, in an exemplary embodiment of the present invention the cladding material on the exiting light side 120 of the sloped fiber end face may be polished, laser ablated or chemically etched to reduce the thickness of the cladding material. The reduced cladding thickness allows the photodetector to be more closely coupled to the fiber core which reduces the beamwidth of the divergent beam that is incident on the photodetector. FIG. 6 graphically illustrates the divergent beam size as a function of cladding thickness. Calculations for a geometrical beam size based on ray optics 130 as well as a distributed beam size 140 that accounts for the Gaussian distribution of the beam are included. The divergent beam size and the corresponding photodetector diameter may be reduced by approximately 50% from a diameter of approximately $25.28\mu m$ to $12.65\mu m$ if the cladding thickness is reduced from a standard thickness of $58\mu m$ to $1\mu m$.

FIG. 7 graphically illustrates an approximate relation between data rate and the diameter of the active area of a

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photodetector as limited by the capacitance of the photodetector. The described exemplary fiber to photodetector interface having a cladding thickness of approximately 1μm may be used in existing

5   optical receiver designs up to a data rate of about 40Gbps when the diameter of the active area is reduced to approximately 12.5μm.

Although a preferred embodiment of the present invention has been described, it should not be construed to limit the scope of

10 the appended claims. For example, the described exemplary fiber to photodetector interface may be utilized in a plastic encapsulated optical receiver rather than the hermetically sealed receiver described herein. Further, those skilled in the art will understand that further modifications may be made to the

15 described embodiment.

For example, the described exemplary fiber to photodetector interface may be used with backside illuminated photodetectors. Referring to FIG. 8, in an alternate embodiment, photodiode 200 may be flip chip mounted to the circuit board 14 as is known in

20 the art. In an exemplary backside illumination embodiment, an n-type layer 204 may again be epitaxially grown on an n-type semiconductor substrate 202. The n-type layer 204 is preferably lattice-matched to the substrate 202 and any intervening layers. In an exemplary embodiment, the n-type layer 204 may be formed

25 of InP and may be doped with a suitable dopant, such as, for example, sulfur.

An active absorber region 206 that is absorptive at the wavelength of interest may be epitaxially formed on the n-type layer 204. The active absorber 206 may be formed from InGaAs or

30 other suitable materials known in the art. In an exemplary embodiment a p-type layer 208 is formed on the active absorber layer 206 from InP. The p-type layer may be doped with a suitable dopant such as Zinc.

However, in the backside illumination embodiment, a received

35 signal is incident upon the substrate. In this embodiment, the

incident light may further diverge as it propagates through the substrate, thereby requiring a larger diameter device to efficiently receive a particular incident beamwidth. Therefore, in an exemplary backside illuminated embodiment, the substrate may be processed to include focusing elements 220 to focus the incident light through the substrate. In one embodiment the focusing elements 220 may be formed by etching approximately 75μm to 100μm radii into the substrate. A wet or preferably a dry etching process such as, for example, reactive ion etching (RIE), reactive ion beam etching (RIBE), or the like, may be used to form the focusing elements.

In the described exemplary embodiment, photodiode 200 may include top side p-type and n-type contacts 210 and 212 respectively. The p-type contact 210 may deposited on the upper surface of the p-type layer 208 that in conjunction with the n-type contact 212 may be used to reverse bias the active absorber layer 206. The p-type contact 210 may be, for example, a gold / zinc (Au/Zn) alloy. The p-type contact may be deposited by electron beam evaporation or other techniques known in the art.

In one embodiment the p-type layer 208 and active absorber layer 206 may be etched, defining an annular opening therein, to expose the upper surface of the n-type layer 204. The n-type contact 212, formed from a metallization such as, for example, Au/Zn, may be deposited on an upper surface of the n-type layer 204 by a lithographic mask and lift-off process. The completed photodiode may be flip chipped mounted to the circuit board 14 as is known in the art.

Referring to the cross section of FIG. 9, a backside illuminated fiber to photodetector interface incorporating a flip chip mounted photodetector of FIG. 8 utilizes an end face slant angle β in the range of about 135-145 degrees. The cladding thickness in the optical path between the photodetector and fiber end face may again be reduced to reduce the separation

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therebetween. The flip chip photodetector may then be used in top mounted photodetector designs as is known in the art.

An exemplary processes for designing a high speed optical interface is illustrated in the flow chart of FIG. 10. In accordance with an exemplary design method, a user may determine fiber parameters 300 such as for example, the index of refraction of the core and cladding. In accordance with an exemplary process, a suitable slant angle in step 302 may then be selected to be less than the critical angle for an end face to air interface determined in accordance with the fiber parameters determined in step 300. A suitable active area diameter for receiving an optical signal having a predetermined data rate in step 304 may then be determined. The diameter of the active area of the photodetector may then be used to determine the separation distance between the fiber end face and the photodetector in step 306.

In one embodiment the separation distance may be chosen so that the active area diameter of the photodetector is substantially equal to or greater than the beamwidth of the divergent beam reflected off the slanted end face of the fiber. The divergent beamwidth may be determined in accordance with the fiber parameters and slant angle of the fiber end face as taught with respect to FIG. 6. The separation distance may then be used to determine the thickness of the fiber cladding material on the exiting light side of the slanted end face in step 308. The fiber may then be polished to reduce the cladding thickness as required in step 310.

One of skill in the art will appreciate that there currently exists many design variations for high speed electro-optic receivers. For example, FIG. 11 illustrates a conventional optical receiver housing 500 having a cavity for receiving a photodetector 502. An optical fiber 504 passes through a small hole in the housing 500. The hole is typically sealed around the optical fiber segment to ensure that the housing is hermetically

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1   sealed. To provide sufficient coupling efficiency a conventional
     package may utilize one or more optical lenses to interface an
     optical fiber to a photodetector.

5   For example, a typical optical lens system may utilize a
     ball lens 506 to focus light exiting from the end face of a
     single mode optical fiber 502 onto a reflecting surface 508. The
     reflecting surface 508 reflects the received light onto a second
     lens 510 that focuses a convergent beam onto a vertically mounted
10   photodetector 502.   Reliable high speed optical communication
     requires accurate optical alignment (i.e. efficient light
     coupling) between the each of the elements in the focusing system
     as well as efficient conversion of photons to electrons.

          In addition, for efficient light coupling the optical image
15   of the fiber end should be closely centered with the
     photodetector active area. However, in conventional focusing
     systems, the relative distance between the end face of the fiber
     (i.e. the object) and the primary focal plane of the sphere will
     affect both the location at which the image is formed as well as
20   the lateral magnification or size of the image. Therefore, the
     assembly distance between the end face of the optical fiber and
     the focal plane of the ball lens as well as the optical alignment
     between the components of the focusing system must be tightly
     controlled for efficient optical coupling between the fiber and
25   the photodetector.

          To maintain proper alignment the optical fiber is generally
     secured at a point inside the housing in addition to being
     secured by the seal at the hole in the housing. In operation
     differential expansion of the fiber segment and the housing due
30   to temperature shifts or mishandling of the housing may cause
     breakage of the fiber segment and or misalignment between the
     fiber and the photodetector.

          In addition, device responsivity may be degraded by the
     imaging processes itself. In a perfect imaging process the
35   principle of the reversibility of light requires that any object

placed at a position previously occupied by its image will be imaged at the position previously occupied by that object. The object and the image are thus said to be interchangeable or conjugates. In this case, the edge of the physical beam image may be very sharp and its size can match the effective active area of the photodetector. However departures from the ideal case may give rise to defects in the image known as aberrations. Lens aberration and mis-alignments in the imaging system may result in non-uniform illumination of the active area of the photodetector as well as variations in the size of the image that result in mismatches between the image and the active area of the device. Such non-uniform illumination of the active area and mismatches between the size of the active area and the size of the image may degrade the responsivity of the device.

For example, there may be some variation in the sensitivity of a photodetector as a function of the position of the incident light in the active area. For example, the light sensitivity of a photodetector may degrade near the periphery of the active area of the device as compared to the center of the active area. In addition, the detector is often sensitive to light outside the active area. The performance of a high speed detector may therefore be improved if the light is restricted to the active area because light incident on other areas of the detector typically creates electron hole pairs that take longer to reach the junction region, degrading the responsivity of the device. Therefore, when the photons are incident near the periphery of the effective active area of the photodetector, the response performance becomes poor and responsivity near the periphery of the effective active area of the photodetector is degraded relative to the responsivity near the center of the device.

Further, the depletion layer for a high speed photodetector is relatively thin, typically on the order of about 0.08-0.15 um for a 10 Gbps device. Therefore, when a non-uniform beam is focused or convergent on the photodetector surface, the depletion

layer may not uniformly absorb the incident photons, wherein high power photons may propagate through the depletion layer without being completely absorbed. The reduced absorption levels can increase the bit error rate and reduce the responsivity of the device.

Therefore, referring to FIG. 12, an alternate embodiment of the present invention may utilize a slant-ended fiber guide 600 in place of the reflecting surface and second lens utilized in conventional systems. The fiber guide may be a pure optical material, such as for example, glass, optical plastic, etc. wherein the environment surrounding the fiber guide (e.g. air having an index of refraction of approximately 1.0) functions as a cladding.

In operation, received light is emitted from the end face of an optical fiber 602 and focused by a lens 604 into the fiber guide 600. The fiber guide propagates a light beam in a manner that is similar to propagation in an optical fiber or waveguide channel. In the described embodiment an end face 606 of the distal end of the fiber guide 600 is non-perpendicular to the longitudinal axis defined by the fiber guide to reflect the beam onto a photodetector 608. As is known in the art the end face of the fiber guide may be cleaved or polished to provide the desired end face angle.

In accordance with the described exemplary alternate embodiment, a metal receiver housing 620 includes a hole for receiving the optical fiber 602. In one embodiment, the lens 604 may be a ball lens that is epoxied bonded to the receiver housing to provide a hermetic seal for the receiver package. In addition, the receiver housing 620 preferably includes a substrate 622, such as for example a silicon substrate that is adapted to retain the fiber guide 600 and to support the photodetector 608.

For example, referring to FIG. 13, the described exemplary silicon substrate may include a recess in the form of a v-groove

630 that is adapted to retain the fiber guide. In the described exemplary embodiment the end face of the fiber guide is slanted at an angle that is less than the critical angle for total internal reflection and is preferably in the range of about 40-55 degrees. The v-groove 630 in the substrate 622 is preferably terminated with a slanted plane 632. The angle of the plane preferably matches the slant angle of the end face of the fiber guide so that the end face of the fiber guide butt fits against the slanted plane of the v-groove. The fiber guide may then be retained within the v-groove and aligned with the photodetector that is mounted on a metal contact pad 634 formed on a surface of the silicon substrate 622.

One of skill in the art will appreciate that reflections off the end face of the fiber guide create a divergent reflected beam whose width increases with increasing distance from the slanted end face 606. Therefore, for a fixed fiber guide diameter the described alternate receiver embodiment may uniformly illuminate a photodetector having a given active area diameter by adjusting the vertical separation between the photodetector and the slanted end face of the fiber guide. Advantageously, the vertical separation between the photodetector and the slanted end face of the fiber guide may be readily controlled by adjusting the height of the surface upon which the photodetector is mounted relative to the slanted termination plane of the v-groove.

The design of a slant ended fiber guide optical receiver may proceed in accordance with the flow chart illustration shown in FIG. 14. To proceed, the initial design parameters including data rate are established 700. As previously described with respect to FIG. 7, the diameter of the active area of a photodetector may now be determined as a function of the desired data rate 710. Next, a user may specify fiber guide parameters, such as for example, the index of refraction of the fiber guide 720. The user may then determine the numerical aperture and critical angle for the specified parameters.

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For example, in one embodiment the fiber guide may be a pure optical material, such as for example, glass, optical plastic, etc. with a refractive index on the order of about 1.52. In this

5 instance the environment surrounding the fiber guide (e.g. air having an index of refraction of approximately 1.0) functions as a cladding. Therefore, the numerical aperture of the fiber guide may be calculated as follows:

$$NA_{FG} = sqrt \; [(n_{core})^2 - (n_{cladding})^2] \cong 1.1447$$

10 In operation, reflections off the slanted end face of the fiber guide create a divergent reflected beam. In the described exemplary embodiment the end face of the fiber is slanted at an angle that is less than the critical angle for total internal reflection and is preferably in the range of about 40-55 degrees

15 730.

In addition, a user may also establish an entrance and exit numerical aperture for the focusing lens 740. A numerical aperture is a measure of the resolving power of a lens, and is a function of the lens geometry and the refractive index of the

20 lens-space medium. In the described exemplary embodiment the exit numerical aperture of the ball lens is preferably chosen to be smaller than the numerical aperture of the fiber guide to promote efficient optical coupling between the ball lens and the fiber guide. In addition, for a spherical ball lens the entrance

25 numerical aperture is equal to the exit numerical aperture. Therefore, the numerical aperture of the ball lens should also be chosen to be larger than the numerical aperture of the single mode optical fiber 740.

For example, the numerical aperture of a typical SMF-28

30 single mode fiber is on the order of about 0.14. Thus, in this example the numerical aperture of the ball lens should therefore be equal to or greater than about 0.14 and much less than 1.1447.

In operation reflections off the end face of the fiber create a divergent reflected beam whose width increases with

35 increasing distance from the slanted end face. As previously

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discussed with regard to FIGS. 4-6, the beam divergence is bound in large part by the maximum angle captured by the fiber guide as limited by the critical angle of the fiber guide or the refraction angles seen at the exit surface of the ball lens. The refraction angle seen at the exit surface of the ball lens is given by the inverse sine of the exit numerical aperture of the ball lens.

$$\text{Refraction Angle} = \sin^{-1}(NA_{Exit})$$
$$= \sin^{-1}(0.2) \cong 11.85°$$

Referring to Eq. 4 below, assuming a 45° end face angle β, the diameter of the fiber guide may be sized in accordance with the diameter of the photodetector and the maximum propagation angle α within the fiber guide. One of skill in the art will appreciate that the maximum propagation angle may be determined either by the critical angle of the fiber guide or more likely by the refraction angle seen at the exit surface of the ball lens.

$$D_{photodetector} = D_{fiberguide}/\tan\{180-(\beta+\alpha)-\beta\} + D_{fiberguide} \qquad (Eq. \ 4)$$

For example, referring back to FIG. 7, the active area diameter of a 10 Gbps photodetector, for example, may be on the order of about 25-35μm depending on the manufacturing process used to produce the device. For purposes of illustration it assumed that the exit numerical aperture of the ball lens is 0.2 and the refraction angle seen at the exit surface determined the maximum propagation angle within the fiber guide and is approximately 11.85°. Therefore, in this embodiment, the diameter of the fiber guide may be determined as follows:

$$35\mu m = D_{fiberguide}/\tan\{180-(56.85)-45\} + D_{fiberguide}$$
$$35\mu m = D_{fiberguide}/4.76 + D_{fiberguide}$$
$$29.16\mu m = D_{fiberguide}$$

One of skill in the art will appreciate that if desired the fiber guide may be coated with a reflective coating to ensure total internal reflection of the rays propagating within the

fiber guide.

Referring to FIG. 15, having determined the diameter of the active area of the photodetector in accordance with the data rate and the corresponding diameter of the fiber guide, the focusing system may be further developed to provide an appropriate lateral magnification to ensure the image of the core of the single mode fiber is efficiently coupled into the fiber guide.

One of skill in the art will appreciate that the lateral magnification and actual image height at the entrance of the fiber guide may now be determined in accordance with a plurality of techniques 770. For example, standardized ray tracing programs that include the affects of spherical aberrations may be used to calculate the size of the actual image at the fiber guide entrance. Alternatively, the size of the image may also be estimated in accordance with para-axial theory and the primary aberration approach as follows:

$$Image = 2 * (lateral\ SA + y')$$

where SA is the spherical aberration and y' is the lateral magnification.

The lateral magnification may be determined in accordance with the Lagrange Invariant as follows:

$$J = n * u * y = n' * u' * y'$$

where in this case, n = 1.0 and n' = 1.0 (both sides of the ball lens bounded by air), so that $u * y = u' * y'$ where u is the object exit NA, u' is the image entrance NA, y is the object height (nine microns total in this example), y': is the image height, i is the incident angle in the 1st medium and i' is the refraction angle in the 2nd medium.

In this example the amplification may therefore be calculated as follows $y' / y = u / u'$ or from the geometrical trace as M= s' / s, where s' and s are the lateral distances between the ball lens and the entrance of the fiber guide and exit of the single mode fiber respectively. In addition, for a spherical focusing lens the object principal plane is overlapped

with the image principal plane so that the amplification may also be defined as M= y'/y. Further, in the described exemplary embodiment the object and image are located in air so that n = 1.0 and n' =1.0 and the magnification may also be determined in accordance with the ratio of the image numerical aperture and the numerical aperture of the lens (i.e. M = u / u'). The numerical aperture of a typical SMF-28 single mode fiber is on the order of about 0.14 so that the amplification factor for a sphere having an exit numerical aperture of 0.2 is given by:

y' = y * u / u' = 4.5 um * 0.14 / 0.2 = 3.14 um,

M = u/u' = 0.14/0.2 = 0.7

In addition, the lateral location of the end face of the single mode fiber relative to the focusing lens as well as the lateral location of the focusing lens relative to the entrance plane of the fiber guide may initially be determined 760. In the described alternate embodiment the entry point of the fiber guide is preferably located at or near the back focal point of the ball lens, allowing the narrowly focused beam to be efficiently captured by the fiber guide. The lateral location of the fiber guide entrance relative to the exit of the ball lens 800 (s') may be determined as follows:

s' = r * i' / u'

= 750 um * 0.573576436 / 0.2 = 2150.911635 um

where for purposes of illustration r, the radius of the sphere, is assumed to be 750 um and i' the sphere refraction angle is assumed to be sin(35°) or approximately 0.57.

Further the lateral location of the end face of the single mode fiber relative to the entrance of the ball lens 802 may determined in accordance as follows:

s = s' /M = 2150.911635 / 0.7 = 3072.730907 um

Further, the lateral spherical aberration may be determined as follows:

lateral SA = |axial SA| * u'_k / (4 * $\sqrt{2}$)

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where the axial spherical aberration may be calculated as
follows:

$$\text{axial SA} = -1/(2 * n'_k * u'_k * u'_k) * \sum_1^k S_I$$

5

where $\sum S_I$ is the primary Seidel Sum given by SI= s* u * n * i *
(i – i') * (i' – u), and k is two indicating either the entrance
or exit interface. For purposes of illustration it may be
assumed that the ball lens has an index of refraction of 1.52 and
10 axial spherical aberration may be approximated by:

$$\text{axial SA} = -1/(2 * n' * u' * u') * \sum_1^k S_I$$
$$= -1/(2 * 1.0 * 0.2 * 0.2)^1 * (11.49 + 9.28)$$
$$= 259.695 \text{ um}$$

15 so that the lateral spherical aberration may be approximated by:

$$\text{lateral SA} = |\text{axial SA}| * u'_k / (4*1.41415926)$$
$$= 259.695 * 0.2 / 5.65685 = 9.181628255$$

Finally the diameter of the image of the 9.0 um core of the
single mode optical fiber core at the entrance of the fiber guide
20 may be approximated as:

$$\text{Image} = 2 * (\text{lateral SA} + y')$$
$$= 2 * (9.181628255 + 3.14)$$
$$= 24.6432 \text{ um}$$

Thus the fiber core image may be focused into the 29 um
25 diameter fiber guide in the 10 Gbps example. However, if the
diameter of the fiber guide is not equal to or greater than the
diameter of the image 780(a) the described exemplary embodiment
may decrement the numerical aperture of the focusing lens 790.
The fiber guide diameter and parameters may again be calculated
30 until the diameter of the fiber guide is equal to or greater than
the diameter of the image at the entrance to the fiber guide to
ensure high optical coupling there between.

As previously discussed the diameter of the active area of
the photodetector decreases with increasing data rate.
35 Therefore, the acceptable range of fiber guide diameters will

also decrease with increasing data rate. One of skill in the art will appreciate that for higher data rate applications, such as for example, 40 Gbps applications, an aspherical focusing lens having a reduced lateral spherical aberration (e.g. in the range of about one micron) may be used to reduce the diameter of the image at the entrance to the fiber guide. The reduced image allows the fiber guide diameter to be sized in accordance with the smaller active area of the photodetector. Alternatively, the fiber guide diameter may taper over the lateral length of the fiber guide. For example, for high speed applications, the fiber guide diameter may taper from a larger entrance diameter that may be required to efficiently capture the image of the core of the single mode optical fiber to a lower diameter that may be preferable for uniformly illuminating the active area of a high speed device.

Although exemplary embodiments of the present invention have been described, they should not be construed to limit the scope of the present invention. Those skilled in the art will understand that various modifications may be made to the described embodiment. Further, the invention described herein will itself suggest to those skilled in the various arts, alternate embodiments and solutions to other tasks and adaptations for other applications. It is the applicants intention to cover by claims all such uses of the invention and those changes and modifications which could be made to the embodiments of the invention herein chosen for the purpose of disclosure without departing from the spirit and scope of the invention.